Types of hydrogen use in transportation and hydrogen refuelling stations

Dr Daniel Symes and Dr Aman Dhir

Centre for Hydrogen & Fuel Cell Research

School of Chemical Engineering

University of Birmingham

Edgbaston

B15 2TT

UK

Abstract

Hydrogen has immense potential as an energy vector. Once produced and stored the energy contained can be exploited in energy generation. This exploitation is thought to be able to rival more traditional methods of energy generation such as coal and gas powered power stations. Typically hydrogen is expected to be deployed in fuel cells, however there exist options in combusting the hydrogen to release the stored energy.

Early markets and economic demand will force the first steps of hydrogen technology. At present road vehicles are seen as the technology of choice, with early adopters keen to take up this technology as we move forward to a low carbon future. Parallel to this is the need to have such an infrastructure to support deployment. In this paper we look at a few of the key areas were hydrogen is in transportation and discuss the infrastructure that is required to support the technology.

Introduction

What is Hydrogen

Hydrogen was first discovered by Cavendish in 1766 [1] and hydrogen internal combustion engines (ICE) trace their roots back to some of the very earliest developments in ICE development [1]. Initially, gaseous fuels like hydrogen were preferred to liquid fuels like gasoline because they were considered safer to work with, due to the low pressures used for the gaseous fuels and the quick dissipation of the gases in the event of a leak. In 1807 Isaac de Rivas built the first hydrogen internal combustion engine, and although the design had serious flaws, it was a more than 50 years ahead of the development of gasoline internal combustion engines [2]. Technological advances in gasoline engines, such as the development of the carburettor, eventually led to other liquid fuels being favoured. Consequently hydrogen was relegated to niche uses, such as in experimental vehicles or in the space program. It wasn't until recently hydrogen has been reconsidered and trialled in internal combustion engines [3].

Compared to nearly all other fuels, hydrogen has a several advantages. Key properties such as it is colourless, odourless, abundant, and energy rich (Gasoline = 48.6 MJ/kg; Hydrogen = 140.4 MJ/kg) make it a highly researched energy vector. Other properties relate its physical properties when combusted.

It must be noted that hydrogen is already used on an industrial scale in other processes not relating to energy, such as, fertiliser manufacture, food processing & electronics manufacture to name a few.

Uses and Properties of Hydrogen

Internal combustion engine (ICE)

The properties of hydrogen make it an ideal energy vector for use as a fuel additive in internal combustion engines to complement the existing gasoline-air combustion. Pure hydrogen ICEs have been researched by Ford and BMW in the 1990s and 2000s but were discontinued.

Flammability

It has wide flammability range:- 4-74% versus 1.4-7.6% volume in air for gasoline. This implies that a wide range of fuel-air mixtures, including a lean mix of fuel to air can be used [4]. Running an engine on a lean mix allows for greater fuel economy due to a more complete combustion of the fuel. In addition, it also allows for a lower combustion temperature, lowering emissions of criteria pollutants such as nitrous oxides (NO_X) [4].

Ignition Energy

Hydrogen has low ignition energy: this is the amount of energy needed to ignite hydrogen, and is an order of a magnitude lower than that needed to ignite gasoline (0.02 MJ for hydrogen versus 0.2 MJ for gasoline) [3]. On the upside, this ensures ignition of lean mixtures and allows for prompt ignition. On the downside, it implies that there is the danger of hot gases or hot spots on the cylinder igniting the fuel, leading to issues with premature ignition and flashback (i.e., ignition after the vehicle is turned off).

Small Quenching Distance

Hydrogen has a small quenching distance (0.6mm for hydrogen versus 2.0mm for gasoline), which refers to the distance from the internal cylinder wall where the combustion flame extinguishes [5]. This implies that it is more difficult to quench a hydrogen flame than the flame of most other fuels, which can increase backfire (i.e., ignition of the engine's exhaust).

High Flame Speed

Hydrogen burns with a high flame speed, allowing hydrogen engines to more closely approach the thermodynamically ideal engine cycle (most efficient fuel-power ratio) when the stoichiometric fuel mix is used. However, when the engine is running lean to improve fuel economy, flame speed slows significantly [6].

High Diffusivity

Hydrogen disperses quickly into air, allowing for a more uniform fuel-air mixture, and a decrease likelihood of majority safety issues from hydrogen leaks.

Low Density

The most important implication of hydrogen's low density is that without significant compression or conversion of hydrogen to a liquid, a very large volume may be necessary to store enough hydrogen to provide an adequate driving range. Low density also implies that the fuel-air mixture has low energy density, which tends to reduce the power output of the engine.

Relevant Trade Offs

Based on the above unique properties of hydrogen, there are several relevant trade-offs pertinent to the use of hydrogen in ICEs.

The first relates to a decision that for the most part has already been made: whether to use a spark-ignition engine design (e.g., most gasoline vehicles), or a compression-ignition (CI) engine design (e.g., diesel vehicles). CI engines work by compressing air in the combustion chamber, increasing its temperature above the auto ignition temperature of the fuel, such that injected fuel ignites immediately and burns rapidly. This small explosion causes the gas to expand and forces the piston down, creating mechanical energy that is be used to power the vehicle. Spark-ignited engines begin combustion at a much lower temperature and pressure through the use of an ignition system that sends a high-voltage spark through a sparkplug to ignite the fuel-air mixture [7].

Spark-ignition engines tend to be less expensive and have lower emissions of criteria pollutants (e.g., NOx and particular matter [4]), but have lower power at low engine speeds and a lower theoretical efficiency than CI engines. Due to hydrogen's wide range of flammability and low density, nearly all recent designs for hydrogen ICE vehicles call for CI engines [7].

A second relevant trade-off is the type of transmission to use. Using hydrogen in a CI engine will most likely require the use of a continuous-variable transmission (CVT), as is commonly used in hybrid gasoline vehicles [8]. The CVT may or may not be designed to be coupled with an electric battery and a separate electric motor that runs off recaptured energy from breaking. Here the tradeoff is between additional cost and improved fuel economy – although most recent hydrogen ICE designs include the battery and separate electric motor [9].

A third trade-off is between power and fuel economy or emissions. Running a hydrogen engine lean reduces criteria pollutants and can improve fuel economy, but it comes at the cost of power due to the lower energy content of the fuel-air mixture. To ensure adequate power, turbo-charging, super-charging, or not running the engine lean can all be used, but are likely to come at a cost of fuel economy and possibly criteria air pollutant emissions [10, 11].

A final key trade-off is between vehicle range and the hydrogen fuel tank size. Efforts are underway to improve storage of hydrogen in fuel tanks through compression or liquefaction of hydrogen, but the low density of hydrogen poses challenges to engineers attempting to decrease the tank size, yet ensure adequate range for hydrogen vehicles. Moreover, the hydrogen storage systems are likely to be heavier than standard gasoline tanks, increasing vehicle weight, which can decrease fuel economy.

Hydrogen / HHO Injection

A number of researchers have reported the benefits of the utilisation of hydrogen in dual fuel engine system [4, 12, 13]. They have shown that there were improvements in terms hydrocarbon (HC), carbon monoxide (CO) and particulate matter (PM) emissions due to ultra low sulfur diesel (ULSD) liquid fuel replacement. All the beneficial effects are due to the hydrogen characteristics such as: absence of carbon, high flame speed, higher diffusivity and broad flammability limits [3, 7]. For example, faster flame speed of hydrogen tends to increase the combustion rate leading to more complete combustion thus suppresses the HC and CO emissions, but NOx emissions can increase.

Challenges

It is widely known that the use of hydrogen in vehicular applications faces some challenges which limit its application.

1. Production
2. Storage
3. Transport

On Demand Production & Consumption

One of the most popular routes that overcomes' the above is the on-board production of hydrogen & consumption for vehicular applications. This method has received increasing attention in the last decade [14, 15]. Here we discuss on-board hydrogen generation via electrolysis. It must be stated that the effects of this addition is also heavily debated as energy is required in the first instance to generate hydrogen, typically this energy comes from the liquid on board fuel. Thus hence you will consume more fuel in the process. It is thought that this technology is better suited to non ECU (electronic control units) engines [16].

Hydrogen and oxygen are generated, on demand, from water, using an electrolysis cell fitted to an alternator. The hydrogen and oxygen gas can be added to any ICE via the air inlet manifold, resulting in faster rates of initiation and subsequent propagation of flames across the whole combustion range [16].

The enhancement of flame initiation and subsequent flame propagation reduces the Ignition delay and combustion period in both spark ignition (e.g. petrol) and compression ignition (e.g. diesel) engines. The chain reaction initiated by the hydrogen and oxygen will cause a simultaneous ignition of all the primary fuel. As it all ignites at once, no flame front can exist and without it there is no pressure wave to create knock [5].

Unburned hydrocarbons, CO and NO, in the exhaust are can be reduced at the same R.P.M. The near absence of carbon monoxide and un-burnt hydrocarbons confirms a very complete and much faster burn [4]. Cooler exhaust temperatures show that more work is taken out during the power stroke. More torque from less fuel at the same engine speeds verifies that higher pressure from a faster burn, acting through a longer effective power stroke, produces more torque and thus more work from less fuel.

The enhanced fuel/air/hydrogen/oxygen mix burns up to 10 times faster however this rapid burn is so fast that the resulting power stroke and exhaust stroke will be much cooler, resulting in less nitrous oxides (NO_x). Reducing hydrocarbons and CO causes a slight rise in the percentage of CO_2 in the exhaust, but as less fuel is used, the actual quantity of CO_2 produced is reduced by roughly the same ratio as the savings in fuel [15]. In brief, noxious gas is almost eliminated and greenhouse gas is decreased in proportion to the reduction in fuel consumption. There have been several studies on this.

Saravanan et al. investigated the hydrogen mixed with air induction in a diesel engine. The findings showed a 27.9% efficiency was achieved without knocking over the entire load range with 30% hydrogen enrichment [17]. They also found that fuel consumption decreased with increasing hydrogen percentage over the operational range. Saravanan also carried out research on hydrogen as a dual fuel for diesel engine system using the exhaust gas recirculation (EGR) technique [18]. The investigation demonstrated that the specific fuel consumption decreased without EGR with a hydrogen flowrate of 20 LPM and it was concluded that the reason for reduction in fuel consumption is the result of the operation of a hydrogen fuelled engine in lean burn conditions.

Adnan et al. investigated a hydrogen injection rate of 20 LPM into the air induction pipe at standard temperature and pressure doubled NOx emission at 1500 RPM in a 7.4kW diesel engine, with a compression ratio of 19.3:1 [19]. The cylinder peak pressure increased by 11% and indicated a power increase of 33% at 1500 RPM. This results in a fuel consumption reduction at fixed load conditions. Consequently however, If the hydrogen was produced on-demand by an electrolyser at 4.4 Wh/L then the added load would be 5.3kW, leaving around 29% of the engines power for useful work, and most likely dramatically increasing diesel consumption [19].

Saravanan et al. investigated optimising manifold injection in a direct injection diesel engine with varying hydrogen flowrates. Their conclusions showed that from manifold injection, the optimised engine condition included the injection of hydrogen at top dead centre (TDC) with injection with a hydrogen flow rate of 7.5 LPM. The brake thermal efficiency increased by 9% compared to normal fuel conditions. CO emissions varied from 0.03 to 0.12 vol% compared to 0.08-0.14 vol% in a diesel fuel investigation [20].

Fuel Cells

Fuel cells are another method in harnessing the energy contained within hydrogen to produce electricity and thus be utilised in an electric powertrain. A fuel cell is an electrochemical device which converts chemical energy into electrical energy, similar to a battery. Batteries and fuel cells belong are also known as galvanic cells, which represent the most direct method for the production of an electrical current via a reaction between chemical substances [24]. Whereas a battery contains a fixed supply of chemical reactants, and therefore has a limited lifetime before it must be discarded or recharged, a fuel cell is supplied by reactants stored externally and will go on producing electrical power for as long as reactants are supplied to it.

This principle was first demonstrated by Sir William Grove in 1839. Grove demonstrated that the hydrogen and oxygen evolved by electrolysis at platinum electrodes immersed in dilute sulphuric acid solution could then be consumed at the same electrodes, with the production of an electrical current: a process which Grove named 'reverse electrolysis' [25].

Generally a fuel cell consists of two electrodes (anode and cathode) separated by an electrolyte. In all cases, a source fuel (usually hydrogen, but hydrocarbon fuels can be used in some variants) is oxidised at the anode, whilst oxygen (usually supplied from ambient air) is reduced at the cathode. The electrolyte charge carrier varies between different types of system, and can be OH^-, H^+, CO_3^{2-} or O^{2-}. Electrons detached from the fuel molecules at the anode flow through an external electrical circuit to the cathode[26]. There are several different types of fuel cell, each having different operating characteristics described briefly below.

Alkaline Fuel Cell (AFC)

The AFC employs an aqueous alkaline electrolyte (typically potassium hydroxide 30 weight% based solution), and is therefore restricted to operating temperatures below 100ºC. The electrolyte is vulnerable to poisoning by CO_2, which means that pure oxygen must be used at the cathode instead of air. Despite this practical limitation, and the fact that the gravimetric power density [kW kg^{-1}] of the AFC is rather low owing to its aqueous electrolyte; AFCs have been employed successfully in specialist applications such as spacecraft [26].

Microbial Fuel Cell (MFC)

The MFC differs significantly from other types of fuel cell in that it employs live bacteria to facilitate the oxidation reaction at the anode, as opposed to an inorganic catalyst. The fuel, or substrate, is typically a carbohydrate or fatty acid but substrates with mixed compositions such as wastewater streams can also be employed. Bacteria live in the anode compartment and oxidise the substrate via normal anaerobic metabolic pathways, producing CO_2, protons and electrons. The MFC cathode is much the same as in an ordinary PEMFC, containing a platinum catalyst to facilitate the reduction of O_2. The MFC has a very low volumetric and gravimetric power density, making them suitable only for stationary applications [27].

Proton Exchange Membrane Fuel Cell (PEMFC)

The PEMFC employs a polymeric membrane as its electrolyte material, which transports protons produced by oxidation of hydrogen at the anode to the cathode, where they participate in the reduction of oxygen, with pure water being the only by-product. The cation-conducting polymer (or ionomer) membrane is typically very thin (~ 20 μm) and light, so that PEM fuel cells have very high power densities. The operating temperature of the PEMFC is governed largely by the membrane material. At present, membranes are typically made from perfluorinated sulfonic acid (PFSA) polymers such as Nafion® or Aquivion, which are limited to less than 80ºC in operation as they rely on liquid water to provide their proton conductivity. Operation at low temperatures demands the use of precious-metal catalysts to facilitate electrode reactions. The development of membrane materials that can operate at higher temperatures (up to 180ºC) is an active area of research. Although precious metal catalysts are still required at these temperatures, they are less prone to poisoning by contaminants, and water management is greatly simplified. The scalability of PEMFCs makes them extremely versatile, with successful demonstrations having been made in stationary power, portable and automotive applications ranging from < 10 W up to 1 MW [26, 28]. This work is concerned with the development of cathode (oxygen reduction) catalysts for the PEMFC.

Direct Methanol Fuel Cell (DMFC)

Methanol can be oxidised by precious metal catalysts and is far easier to store and handle than hydrogen, making it convenient for use as an anode reactant in fuel cells. DMFCs employ polymeric membranes akin to hydrogen-fuelled PEMFCs, although they are usually thicker to limit the crossover of methanol to the cathode, which lowers the efficiency of the cell. Despite the advantages of methanol as a fuel, DMFCs are limited to low-power applications because their power output (and therefore their power density) is limited by the relatively slow reaction kinetics of the methanol oxidation reaction compared to hydrogen oxidation. Additionally, the oxidation of methanol produces CO_2 as a by-product, meaning that DMFCs do not share the zero emission credentials of hydrogen-fuelled PEMFCs, and platinum catalysts are effectively poisoned by CO produced as an intermediate in the anode reaction, so CO-tolerant catalysts are necessary. Variants of the DMFC include the DEFC (Direct Ethanol Fuel Cell), and DBFC (Direct Borohydride Fuel Cell), which employ ethanol and sodium borohydride solution as the anode reactant respectively [26].

Phosphoric Acid Fuel Cell (PAFC)

Molten phosphoric acid (H_3PO_4) at between 150-200ºC serves as the electrolyte in the PAFC. Whilst Pt-based electrocatalysts are still required on both electrodes, the high operating temperature makes them particularly tolerant to CO poisoning, meaning that reformate hydrogen can be utilised as the anode reactant with minimal purification. However, the high operating temperature and chemically-aggressive electrolyte present a significant challenge from a materials durability perspective, and together with slow start-up and low power density this makes the PAFC unsuitable for applications other than large-scale stationary power generation: a field in which PAFCs have been successfully deployed, albeit in small volumes, with units reported to have achieved 30,000 hours operation [26].

Molten Carbonate Fuel Cell (MCFC)

Similar to the PAFC, the MCFC uses a molten sodium- or lithium carbonate electrolyte, which requires an operating temperature of around 650ºC. At such high temperatures, precious metal catalysts can be substituted for inexpensive alternatives such as Raney nickel, and hydrocarbon fuels such as methane or propane become viable for use as anode reactants. However the same durability and start-up issues suffered by the PAFC also apply to the MCFC, meaning that they are suitable only for large-scale stationary applications [26].

Solid Oxide Fuel Cell (SOFC)

The SOFC has the highest operating temperature of any fuel cell variant, requiring temperatures up to 1000ºC for its ceramic electrolyte to conduct O^{2-} ions from cathode to anode. Inexpensive catalysts (typically nickel) can be utilised, as well as hydrocarbon fuels [29, 30]. The extreme operating temperature allows easy recovery of waste heat, so that SOFCs are particularly suitable for combined heat and power (CHP) systems. Early designs employing planar electrodes suffered from issues of slow start-up and poor durability toward thermal cycling, but these problems have been diminished by the advent of tubular and micro-tubular cell geometries. Whilst materials durability remains a significant challenge in the development of SOFCs, commercial products are already beginning to emerge for industrial and residential CHP applications [31].

Hydrogen Refuelling Infrastructure

With early adopters, the evolution of a fuel cell vehicle market has pushed the requirement of an infrastructure of hydrogen refuelling stations across Europe and the world. There are approximately 13 hydrogen refuelling stations operational in the UK with several in planning [32, 33] and approximately 55 in Europe. With currently approximately another 100 in planning for construction of a backbone hydrogen refuelling network connecting major metropolitan areas in the European continent.

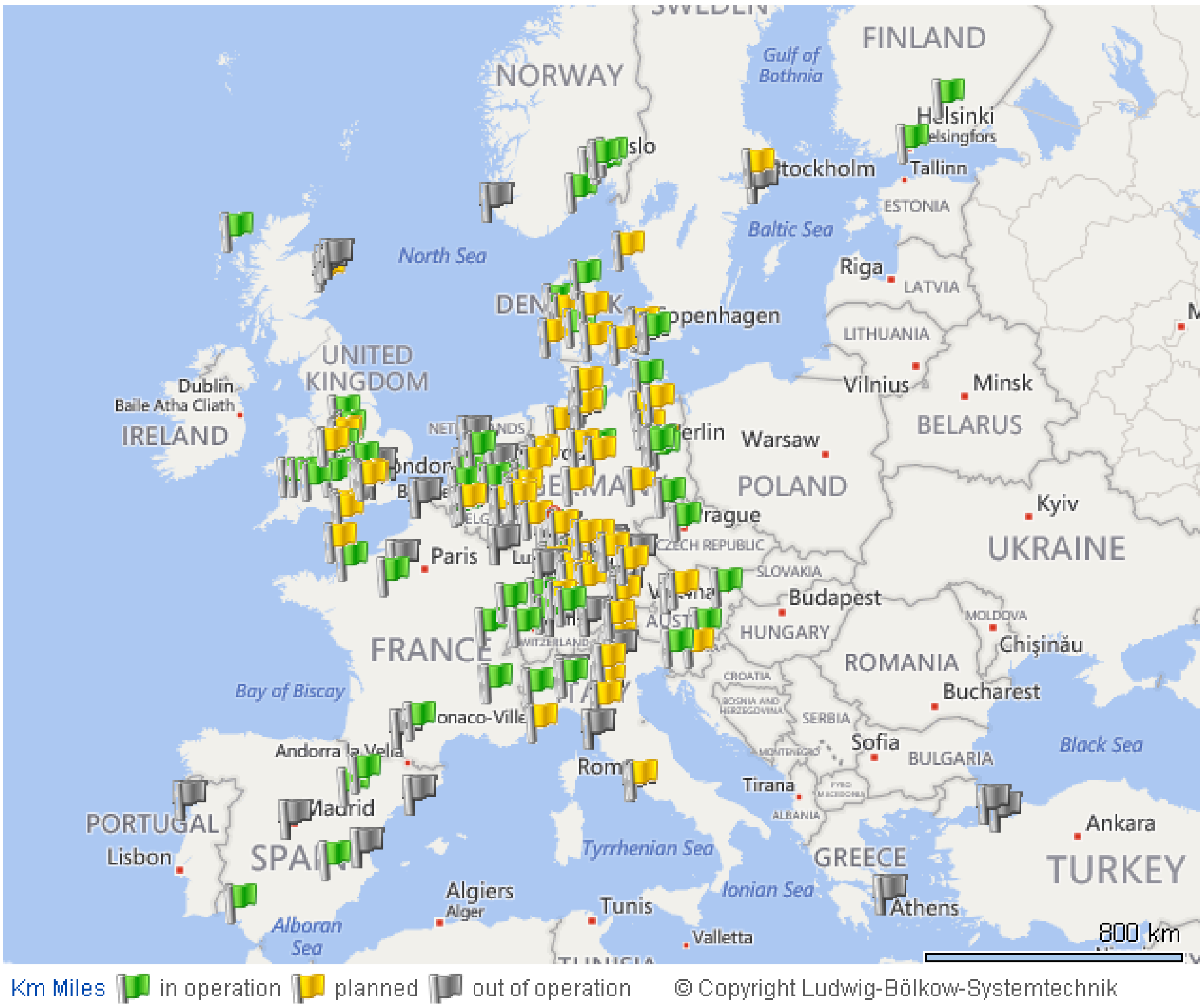

Figure 1Map of European Hydrogen Refuelling stations [33]

Fixed Stations

Hydrogen refuelling stations can be constructed in various ways. There is the options for stations make their fuel onsite [34], whilst others store gas locally [35]. Each option requires equipment for storing, compressing and dispensing hydrogen. Currently the storage tanks must be above ground, although codes for underground storage are in the planning stages. Some existing stations store hydrogen on the canopy of the station.

At liquid storage stations [36], hydrogen is produced offsite and cooled to become a liquid. A tanker truck transfers the hydrogen to the refuelling station and fills the storage tank. To be a liquid, hydrogen must be at a cryogenic temperature (-423°F). The storage tank is thermally insulated meaning that it doesn't require any further energy input.

When a customer activates the hydrogen dispenser, the hydrogen flows from the storage tank through pipes that can be above or below ground. If the driver is dispensing hydrogen at 350bar, the fuel goes directly into the vehicle. If the driver is dispensing hydrogen at 700bar, the hydrogen first goes into another compressor where the hydrogen is pre-cooled and compressed further before dispensing. To avoid confusion, the nozzles are different for 350bar and 700bar hydrogen.

Other stations offer hydrogen that is delivered as a gas. The hydrogen is compressed and packed into cylinders at the point of production offsite. A haulage truck brings a trailer to the refuelling station where the hydrogen is pumped to onsite buffer storage or the truck leaves the storage cylinders or the whole trailer in a designated area. The driver connects a feed on the cylinders to the pipes that are connected to the buffer storage. Although a gaseous station requires significantly less equipment, it cannot store as much hydrogen and the tube-trailer location must be integrated into the site design if this is a refuelling station design requirement.

An alternative option is to make hydrogen on site at the refuelling station. Refuelling stations can have small reformers that use natural gas or biogas to make hydrogen onsite. The reformer is usually within a small building and the equipment to purify, compress and store the hydrogen is in the near proximity [37].

Onsite production refuelling stations can also use electrolysers and solar panels / wind turbines to make hydrogen from water and electricity. The equipment to produce, compress and store the hydrogen can be on the forecourt or on the canopy of the refuelling station. Solar panel and wind turbines are connected to the national electricity grid producing electricity when demand is greater than supply on the grid (deficit) and producing hydrogen via electrolysis when supply is greater than demand on the grid (surplus) [37].

Fixed/Mobile

Central, semi-central, and distributed production facilities are expected to play a role in the evolution and long-term use of hydrogen as an energy carrier. The different resources and processes used to produce hydrogen may be suitable to one or more of these scales of production. Examples of such station are being deployed and test by UK company ITM Power [34]

Distributed System

Hydrogen can be produced in small units where it is needed, such as vehicle refuelling stations, in a manner known as "distributed production." Distributed production may be the most viable approach for introducing hydrogen in the near term in part because the initial demand for hydrogen will be low. Two distributed hydrogen production technologies that may offer potential for development and commercialization are 1) reforming natural gas or liquid fuels, including renewable liquids, such as ethanol and bio-oil, and 2) small-scale water electrolysis [38].

Centralised System

Large central hydrogen production facilities (750,000 kg/day) that take advantage of economies of scale will be needed in the long term to meet the expected large hydrogen demand. Compared with distributed production, centralized production will require more capital investment as well as a substantial hydrogen transport and delivery infrastructure [39].

Half/Half System

Intermediate-size hydrogen production facilities (5,000–50,000 kg/day) located in close proximity (25–100 miles) to the point of use may play an important role in the long-term use of hydrogen as an energy carrier. These facilities can provide not only a level of economy of scale but also minimize hydrogen transport costs and infrastructure [39].

Summary of Stations

Larger, centralized facilities can produce hydrogen at relatively low costs due to economies of scale, but the delivery costs for centrally produced hydrogen are higher than the delivery costs for semi-central or distributed production options (because the point of use is farther away). In comparison, distributed production facilities have relatively low delivery costs, but the hydrogen production costs are likely to be higher—lower volume production means higher equipment costs on a per-unit-of-hydrogen basis.

Key challenges to hydrogen delivery include reducing delivery cost, increasing energy efficiency, maintaining hydrogen purity, and minimizing hydrogen leakage. Further research is needed to analyse the trade-offs between the hydrogen production options and the hydrogen delivery options taken together as a system. Building a national hydrogen delivery infrastructure is a big challenge. It will take time to develop and will likely include combinations of various technologies. Delivery infrastructure needs and resources will vary by region and type of market (e.g., urban, interstate, or rural). Infrastructure options will also evolve as the demand for hydrogen grows and as delivery technologies develop and improve.

Capacity

Existing hydrogen fuelling stations have a vast discrepancy in delivery capacity. For example UC Irvine’s fuelling station has on-site storage of only 25kg per day, which wouldn’t be capable of providing more than a full refill to approximately 15 fuel cell vehicles. However newer stations [40] are capable of delivering 750 kg/day of hydrogen [39]. The typical sizes anticipated for an initial hydrogen refuelling network range from 100kg/day for portable stations (ISO containers) to 1000kg/day for the larger refuelling stations.

Semi-permanent hydrogen refuelling stations can produce around 50-100kg of hydrogen a day, which is enough to fill 10-20 cars a day. These are often built in standard size ISO 20ft containers, and are expandable by adding extra units [34]. This makes them very attractive for early stage implementation. There are limits to the number of users for each station and the number required to meet the demand at later stages would be prohibitive. Hydrogen can either be produced on site by electrolysis, or trucked to the station, the trailer is often used as the onsite hydrogen storage and swapped with a full one when required. These stations have been chosen for the initial stages of infrastructure, as they are quick to build and can be moved as the infrastructure grows. We will use portable stations to create an instant skeleton network while permanent stations are being built.

Figure 2: ITM Power semi-permanent refuelling station [34],

These are like traditional gas stations, the hydrogen can either be produced on or off-site. These take much longer to plan and build and the capital costs for a permanent station are much higher than for semi-permanent stations.

Hydrogen Transportation

The capabilities of the different techniques for distributing hydrogen have a large impact on the methods suggested for producing hydrogen and in the strategic placement of some refuelling sites. When considering hydrogen transportation it must be noted that for some refuelling sites, onsite generation of hydrogen may be preferential to off-site generation [41-43]. This might be the case when considering locations local to municipal waste site, areas of large biomass production, or where the delivery of hydrogen is impractical. In these cases different goods often need to be transported to and from sites. Here we only consider the transportation of hydrogen and the implications this has on refuelling locations [44]. There are 3 main hydrogen transport mechanisms; gaseous trucked, gaseous piped, and liquid trucked. Here we only consider gaseous transport. The reason, the energy cost of liquefaction is very high, compressing hydrogen to 35 MPa or 70 MPa requires 1.05 or 1.36 kWh/kg H_2 respectively, whereas cryogenic hydrogen storage requires 10-13 kWh/kg H_2 [45].

Transporting Compressed Gas Hydrogen by Truck

The transportation of hydrogen in the form of compressed gas canisters is by far the most commercially exploited so far [46, 47]. The exact costing of this delivery method is dependent on the nature of freight (road, rail or ship) and the length of the journey. Delivering hydrogen by truck is limited by the size of the trucks. Up to 250kg of hydrogen can be delivered in the largest hydrogen trucks which means that unless multiple refuelling's per day are required for medium and large stations and it has been assumed that these can't be refuelled by truck. It is also unfeasible to deliver hydrogen over 200km by hydrogen truck. This presents significant hurdles to the strategic roll out of a hydrogen infrastructure.

Transporting Compressed Gas Hydrogen by Pipe

The transportation of hydrogen via pipe has been touted as a long term goal in establishing the hydrogen economy. Several locations already operate with piped hydrogen as the feed for refuelling stations, such as the southern California example [38, 48]. The similarities between piped hydrogen and already established networks such as natural gas and long established engineering principles in the area through extensive chemical engineering use of piped hydrogen make the proposition less daunting. Piped hydrogen doesn't have the same capacity restrictions that a trucked hydrogen delivery infrastructure will have, however it has very large capital costs and takes a long time to build so is an option when large quantities of hydrogen are being delivered. However it must be planned and started much earlier than it is required.

Components

This section lists the various components found at a hydrogen refuelling station [37].

Low Pressure Storage

When delivered onsite to the hydrogen refuelling station, the hydrogen is at low pressure (15bar to 200 bar). This buffer storage is held and to constantly supply the compressor thus continuously creating high pressure (400bar for example) hydrogen.

Since the hydrogen is at low pressure, a vast volume of storage is required to accommodate this hydrogen delivered or generated at the refuelling station.

Compressors

To increase the pressure of the hydrogen to the requirements of a hydrogen fuel cell vehicle (to 400 bar for a 350 bar fuel cell vehicle and 800 bar for a 700 bar fuel cell vehicle), one or many onsite compressors are required for this to occur. The number of compressors is dependent on the compression rate of the hydrogen.

Hydrogen compressors are usually driven electrically or by compressed air. Compressed air driven compressors represent a safer option than electrically driven, since the reduced risk of fires and sources of ignition. This does however require an additional store of compressed gas on site which is an additional cost and requires space which is at a premium on a hydrogen refuelling station.

High Pressure Storage

After compression of the hydrogen gas, it is stored in high pressure gas storage tanks/cylinders. These storage tanks are typically lined with carbon fibre and Kevlar to prevent hydrogen leakage, embrittlement and maintain health and safety protocol at a hydrogen refuelling station.

Delivery Mechanism

International fuelling protocols exist so that hydrogen is supplied to a hydrogen storage system quickly and to a high state of charge (SOC). It also maintains that a storage system operating limits (of 85^{o}C for the internal tank) don't overheat or never overfill (exceed 100% SOC [density = 40.2 grams / litre]).

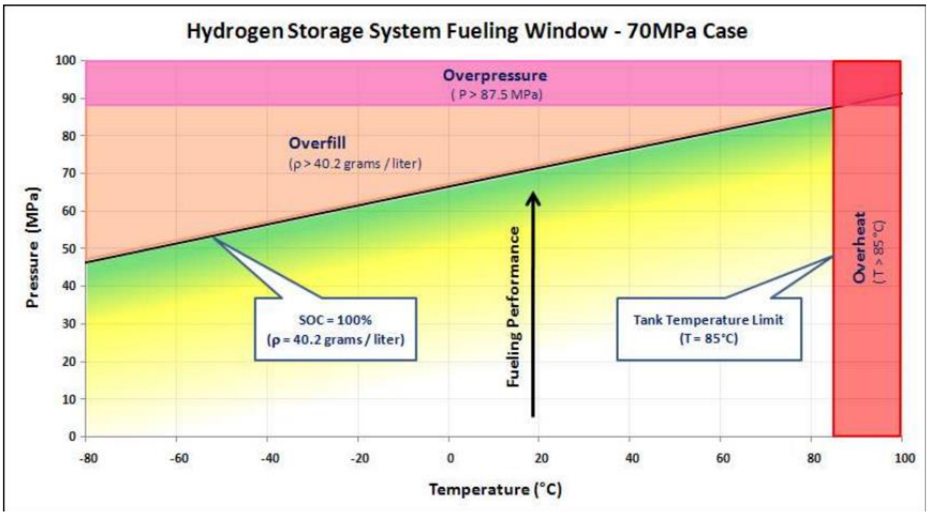

Figure 3: Hydrogen fueling window [49]

SAE-J2601 was established in 2012 to ensure these fuelling protocols are met. There are three derivatives of this protocol. J2601-2 (HD) hydrogen vehicle refuelling guideline for 350 bar bus and heavy duty vehicles (>10kg) and J2601-3 (FL) hydrogen vehicle refuelling standard for 250 and 350 bar forklifts with small fuel tanks.

J2601 also defines the refuelling station dispenser type by capability to dispense hydrogen fuel at a specific nozzle pre-cooled temperature. There is a direct relation between pre-cooling and refuelling speed.

- Type "A"- Dispenser has -40℃ pre-cooling (70 & 35 MPa)
- Type "B"- Dispenser has -20℃ pre-cooling (70 & 35 MPa)
- Type "C"- Dispenser has 0℃ pre-cooling (35 MPa only)

- Type “D”- Dispenser has no pre-cooling (35 MPa only)

There are many codes and standards that dictate the build, design and location of filling stations, more information on this can be found in various documents [50-56]

Conclusions

In this paper we have introduced hydrogen as an energy source. We have focussed on how it is used in transportation and the development of an infrastructure to support deployment of vehicles. Hydrogen can be utilised in a variety of applications, here we discussed how ICE and fuel cells can be used and some of the limitations with the technology. It has been discussed that hydrogen can be utilised, produced and delivered in a variety of ways, highlighting the key components that are needed to deliver a hydrogen economy for transport, through the use of refuelling stations.

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